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Electromagnetic Design of Feedhorn-coupled Transition-Edge Sensors for Cosmic Microwave Background Polarimetery

07.31.2011

Keywords Transition-Edge Sensors, Cosmic Microwave Background, Polarimetry

Abstract Observations of the cosmic microwave background (CMB) provide a powerful tool for probing the evolution of the early universe. Specifically, precision measurement of the polarization of the CMB enables a direct test for cosmic inflation. A key technological element on the path to the measurement of this faint signal is the capability to produce large format arrays of background-limited detectors. We describe the electromagnetic design of feedhorn-coupled, TES-based sensors. Each linear orthogonal polarization from the feedhorn is coupled to a superconducting microstrip line via a symmetric planar orthomode transducer (OMT). The symmetric OMT design allows for highly-symmetric beams with low cross-polarization over a wide bandwidth. In addition, this architecture enables a single microstrip filter to define the passband for each polarization. Care has been taken in the design to eliminate stray coupling paths to the absorbers. These detectors will be fielded in the Cosmology Large Angular Scale Surveyor (CLASS).

PACS numbers:

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1 Introduction

Recent observations in cosmology have hinted that the universe experienced a brief period of rapid expansion called inflation early in its history that is believed to be responsible for the flatness of the universe and the origin of structure. If inflation occurred, it would have produced a gravitational wave background that is evidenced by a small but distinct polarized signature on the cosmic microwave background. For the simplest models of inflation, the signal is expected to be $\sim 10^{-8} - 10^{-9}$ times that of the isotropic 2.7K CMB. To make a successful measurement down to this sensitivity, both a large number of background-limited sensors and good control of systematic effects are required. The sensors described in this work address these criteria and will be implemented in the Cosmology Large Angular Scale Surveyor (CLASS).

2 Sensor Overview

The architecture of the sensor is illustrated in Figure 1. Feedhorns are used to provide well-controlled symmetric angular response through the optics. A symmetric planar orthomode transducer (OMT) is utilized to couple the orthogonal linear polarizations at the throat of the feedhorn into independent superconducting microstrip transmission lines. A band-defining filter limits the spectral range for each of the horizontal and vertical polarizations. The signals terminate in resistors thermally coupled to Transition-Edge Sensors (TES) that are capable of providing background-limited performance. The TES is located on a leg-isolated membrane; the geometry of the legs determines the thermal conductance which in turn sets the noise and saturation power for the sensor. The design is scalable to both large focal plane sizes necessary to achieve the requisite sensitivity and multiple frequencies required to extract the inflationary signal from polarized Galactic foregrounds.

3 Feedhorns and Photonic Chokes

A smooth-walled feedhorn with low cross-polarization across a wide bandwidth [1] is used to couple the sensor to the instrument optics. The measured performance is comparable to that of an equivalent corrugated structure. This feed has a monotonic profile such that it is compatible with a plunge drilling manufacturing process that enables large number of such feeds to be tiled in a focal plane. The feed structure also provides a low-frequency cutoff that eliminates low-frequency out-of-band optical response.

At the throat of the feedhorn, the detector chip is positioned parallel to the polarization direction. A photonic choke defines the volume in which the microstrip circuitry resides. This device employs a two-dimensional pattern of metallic pillars to place a virtual short at the waveguide wall. It can be used to prevent leakage at the interface between the waveguide and the surface of the chip while simultaneously providing a thermal break if required. Photonic choke designs have been demonstrated and reported elsewhere. [2]

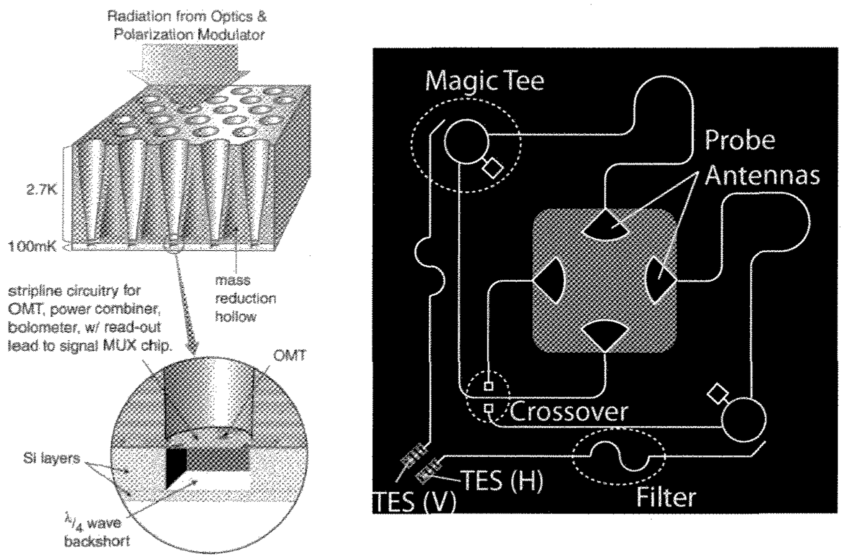

Fig. 1 (Color Online) The detector architecture combines the beam forming properties of HE_{11} feedhorns with the sensitivity of transition-edge sensors. The symmetrized approach implemented in the planar circuitry allows each polarization to be processed by a single on-chip filter.

4 Planar OMT

An OMT is a polarization diplexer that separates the radiation signal into the horizontal and vertical polarized components for detection.[3] Historically, waveguide-based devices performing this function over a broad bandwidth have been inherently three-dimensional. The approach described here realizes the desired coupling and diplexing performance as a symmetric planar structure.[4,5] A compact planar design enables packaging a large number of sensors for CMB polarimetry. Our implementation is based on niobium (Nb) superconducting microstrip lines on 5 μm thick monocrystalline silicon substrate. At these wavelengths, the superconductor loss is subdominant to dielectric loss for even the best dielectrics. We use monocrystaline silicon dielectric for its superior dielectric properties and compatibility with silicon micromachining processes.

The purpose of the OMT is to process each single mode polarization independently. Although suborbital platforms only utilize a portion of the full waveguide band, the OMT is designed for single mode operation between the waveguide cutoff and twice this frequency. In this frequency band six waveguide modes can exist in the structure. By differencing the signals from opposing probes with the magic-tee, the four undesired modes are suppressed. The two remaining modes carry the information from the two orthogonal polarizations on the sky. The OMT couples each of these to an independent microstrip line. A variation on this theme is being employed in the ACTpol, SPTpol, and ABS instruments[6] that combine the signals from opposite probes antisymmetrically directly into the resistor. A key difference

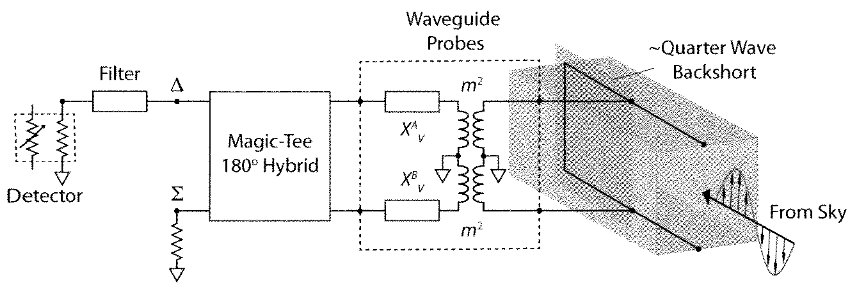

Fig. 2 (Color Online) A circuit model for the OMT with a filter and detector is shown.

in the described approach is that signals from the probes can be combined before filtering, thus the signal band is uniquely defined for a given polarization.

A circuit diagram representing the OMT is shown in Figure 2. The waveguide probes serve as an impedance transformer between the waveguide and microstrip. The transformer turn ratio, m, can be computed from the overlap integral of the fields in guide and currents excited by the waveguide probes. Two such probes are used to sense a single polarization. A waveguide backshort is used to compensate the reactances in the probes and minimize reflection. The magic-tee combines the signals from opposite probes into a single microstrip. The signal from the desired waveguide mode propagates to the difference port (Δ). The sum port (Σ) terminates the residual symmetric modes while maintaining high inter-channel signal (polarization) isolation. In addition to providing high isolation, the 180° hybrid provides phase and amplitude match of $\pm 1^\circ$ and ± 0.5 dB, respectively over 75% of the operating frequency bandwidth.[7]

A via-less crossover[8] allows the microstrip line containing vertical and horizontal signal to cross in the plane of the detector chip using the existing microstrip layer and its ground layer. The use of the crossovers allows the microstrip structures skyward of the magic-tees to be symmetrized, thereby providing control over the relative phase of the two lines.

5 Band-defining Filters

An ultra-wide band rejection filter is used after the OMT to reject signals reactively in the stop-band (from $\sim$50 GHz to $\sim$700 GHz). Above the niobium superconducting gap frequency at 700 GHz signals are attenuated. The signal rejection in the frequency band up to 700 GHz is performed by cascading three stepped impedance low pass filters. This approach has been demonstrated at low frequencies.[9] The complete system design has been modeled and we find that the combined out-of band rejection from 50 GHz to 700 GHz is better than -65 dB.

The OMT design performs over a full waveguide band, 30 to 50 GHz, which is ideal for a space mission. In this environment, large bandwidths increase signal-to-noise. For CLASS, atmospheric and optical issues motivate limiting the bandpass of the detector between 33 and 43 GHz using on-chip filtering. The response of the system with this band-limiting is compared to that of the OMT for the full waveguide band in Figure 3A.

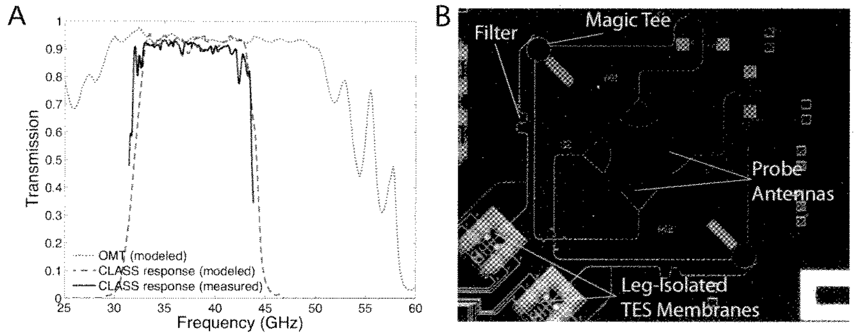

Fig. 3 (Color Online) A.The modeled average $(H+V)/2$ OMT response over the full waveguide band is shown along with the same quantity for the band-limited case. The measured average response is also shown. B. Prototype detector chips have been completed for the 40 GHz CLASS channel.

6 TES Membrane

Also residing on the detector chip, the TESs are used for detection of the horizontally- and vertically-polarized signals. From the filters, the microstrip continues across narrow legs onto a membrane that supports a TES. It is transformed to a lower characteristic impedance using a compact impedance transformer.[10] The line is terminated using a 5 Ω PdAu resistor connected to gold bars on the TES. Power is thermalized in the resistor and conducted to the TES bolometer via electronic conduction. Each detector bias lead consists of two stepped impedance stubs that together serve as a microwave virtual ground for the resistor over the signal band. The bias leads continue as alternating high and low impedance microstrip chokes that prevent the loss of signal power.

We have made detailed electromagnetic simulations of the performance of the microwave coupling across the legs, through the transformer, and into the termination. The design of the MoAu TES detector with interdigitated Au "zebra stripe" normal metal bars is similar to those implemented in the Atacama Cosmology Telescope.[11] To achieve the noise performance and saturation power required by CLASS, the superconducting transition temperature is 150 mK.

7 Out-of-Band Radiation Control

Control over the out-of-band response is an important consideration for reaching ultimate background limited performance for a bolometric detector. The specific environment of the detector defines the details of the required filter design e.g., for ground-based applications thermal blocking filters would be in the optical path to control the thermal load, however, for a cooled telescope in space such requirements are significantly relaxed. The detector's out-of-band response has two parts: a component that results from direct propagation down the guiding structures and an indirect radiative coupling to the environment. Both of these terms need to be addressed by the design. The response in the guiding structures is defined by the

on-chip reflective filtering and above the superconducting gap frequency is attenuated by the resistive properties of the planar transmission lines. The radiative component, on the other hand, is inherently three-dimension in nature. The choice of the enclosure geometry and material properties to control this component.

Recent experiments in which planar microstrip filters are integrated with detectors have experienced a spurious high frequency component, or so-called "blue leak," response, where significant power is coupled to the detector at frequencies > 3 times the design frequency.[12,6] These observations have been traced to unintended coupling between the millimeter-wave transmission line structures, bias circuit traces, and the incident radiation field. Although the details of this problem are specific to the exact implementation, in the approach explored here, unwanted coupling is limited by controlling the propagation of the mode set in use for transmission, selectively reflecting the undesired radiation (e.g., through optical filters, grill filters, waveguide cutoff), or absorption of such signals on appropriately tailored terminations.

8 Circuit Validation

In order to validate the microwave circuitry on the chip, devices have been produced in which the two polarizations are coupled on the detector side of the filter. The chip is placed in a dewar and cooled to $\sim 2K$. Wavguides connect the cold circuitry to the warm network analyzer. The calibration is reliable to $\sim 0.5\,dB$. We have observed an increase in transmission as the temperature decreases. Initial results for the in-band average $(H+V)/2$ transmission are shown in Figure 3A overlaid on the modeled response.

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